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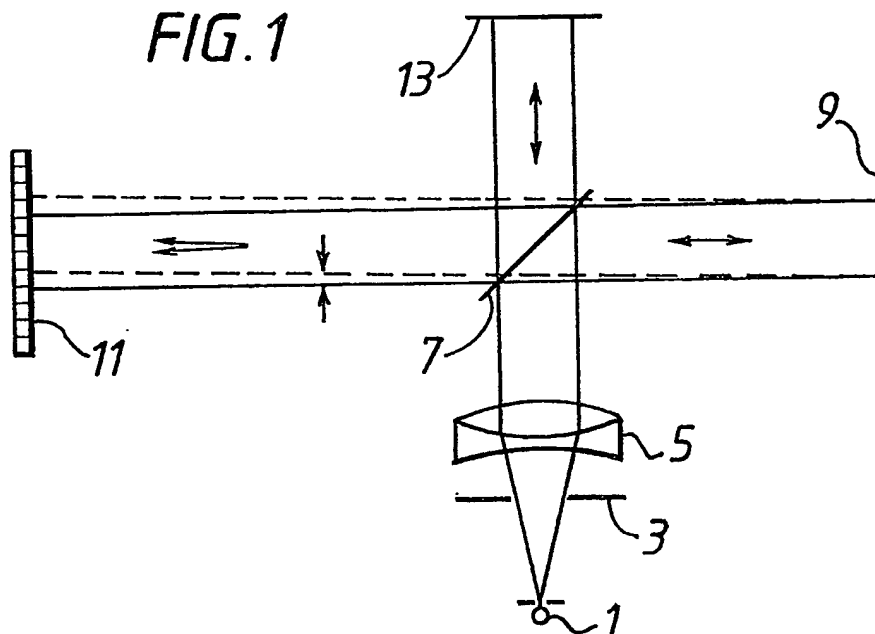|	
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(54) Light beam angle detection

(57) A system for measuring the angle of a light beam is arranged so that a periodic pattern is formed on a photodetector 11, e.g. a CCD array, with a waveform property such as wavelength or phase varying with the angle of the light. This may be done by creating interference between the light beam and a reference light beam, or by forming a shadow on the detector array 11 of one or more masks 23, 25 having a periodic transmission characteristic. One convenient way of processing the output of the photodetector array is to perform an FFT to obtain spatial frequency components, and extract therefrom the angle of the light beam. A substantial length of the array is used in any particular measurement which smooths inter-element performance differences. The system may be used to measure the inclination of mirror 9.
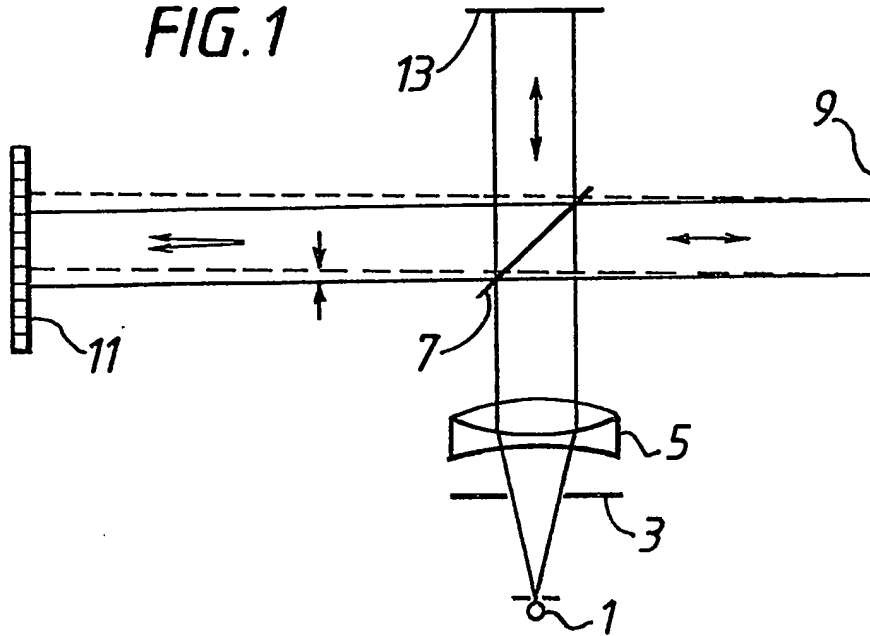

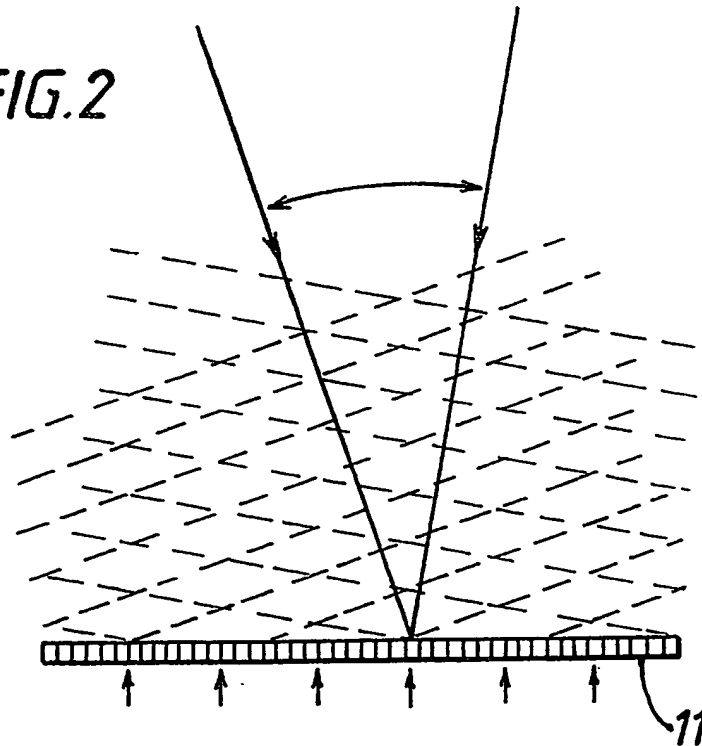
FIG.1

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FIG.1

FIG.2

FIG.3

11 CCD
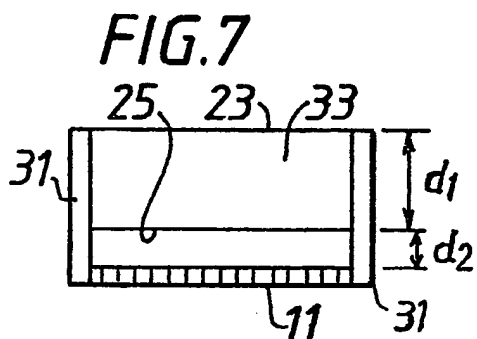
15 CPU

17 LUT

FFT 19

O/P 21

FIG.6

29 25 23 27

31

d_1

d_2

11 31

FIG.8

23

33

11

FIG.7

25 23 33

31

d_1

d_2

11 31

43

35

39

41

37

FIG.11

FIG.4

FIG.5

FIG.9

d

7

13

11   23

5

3

1

FIG.10

23

11

d
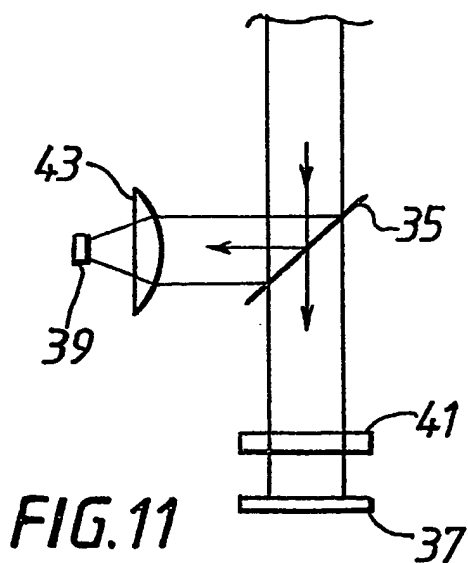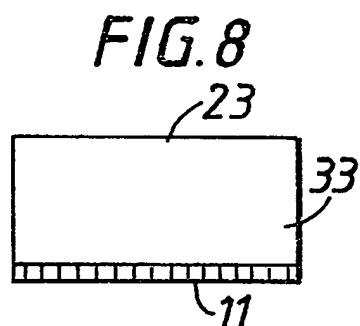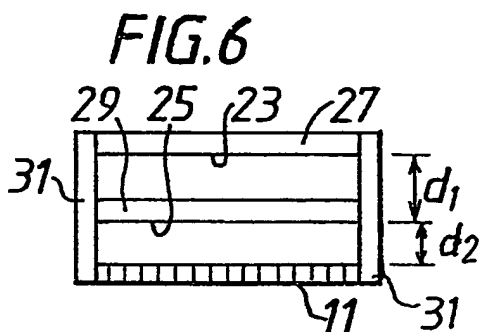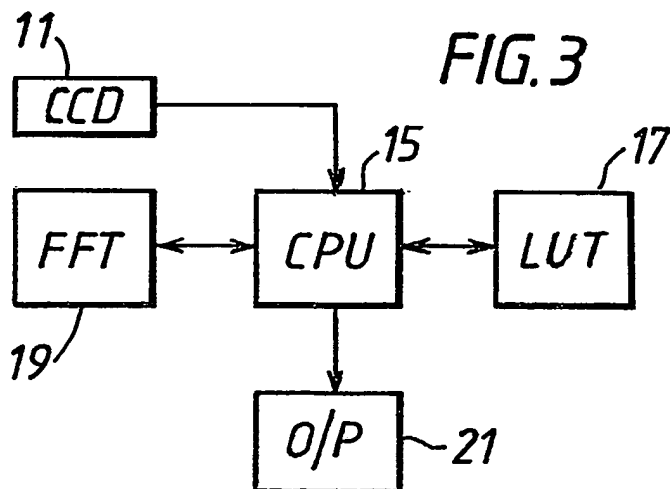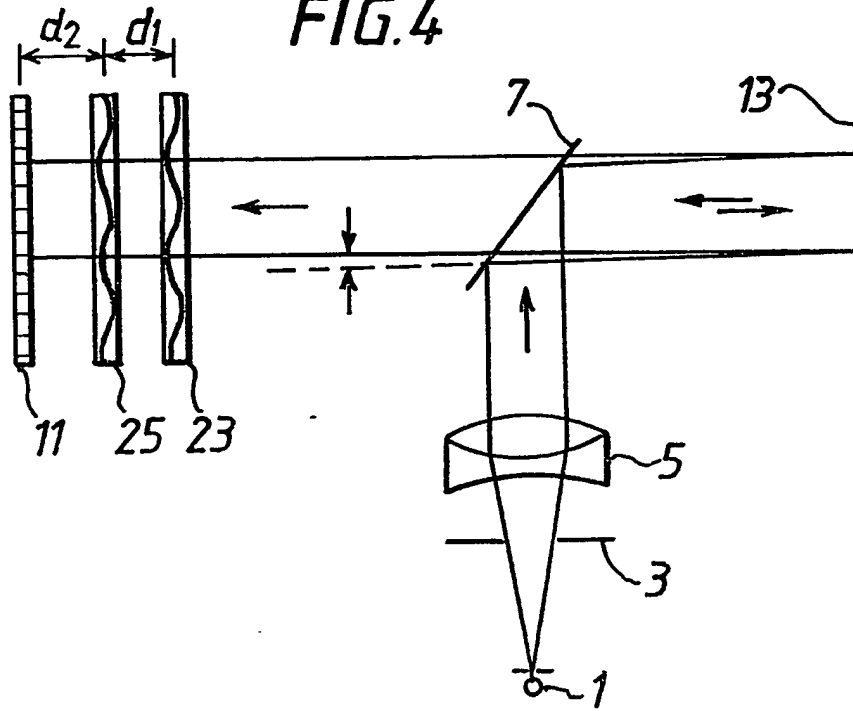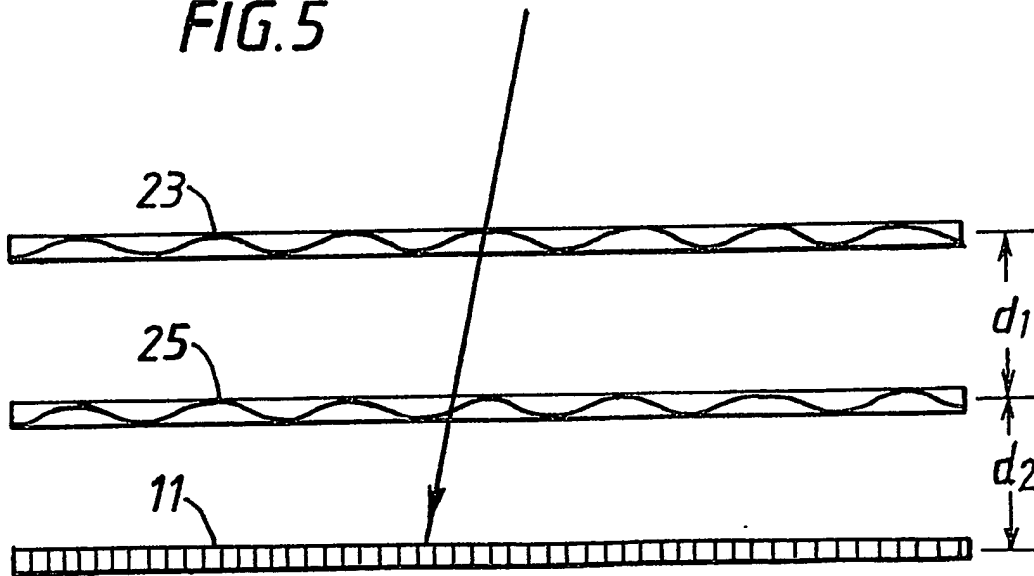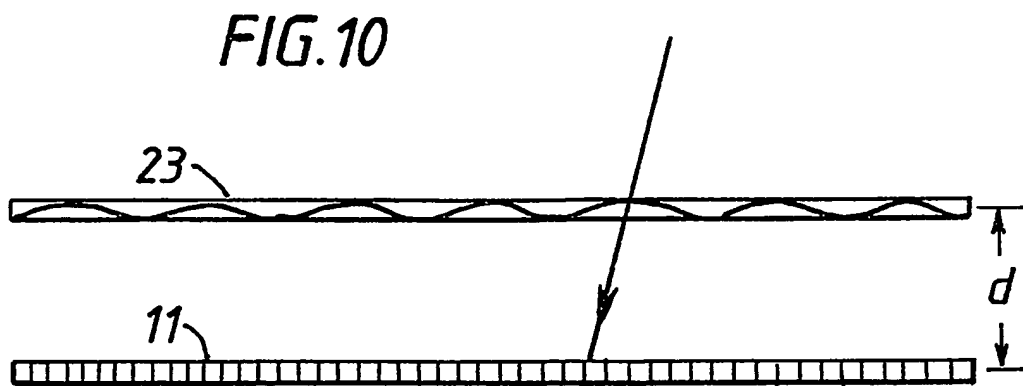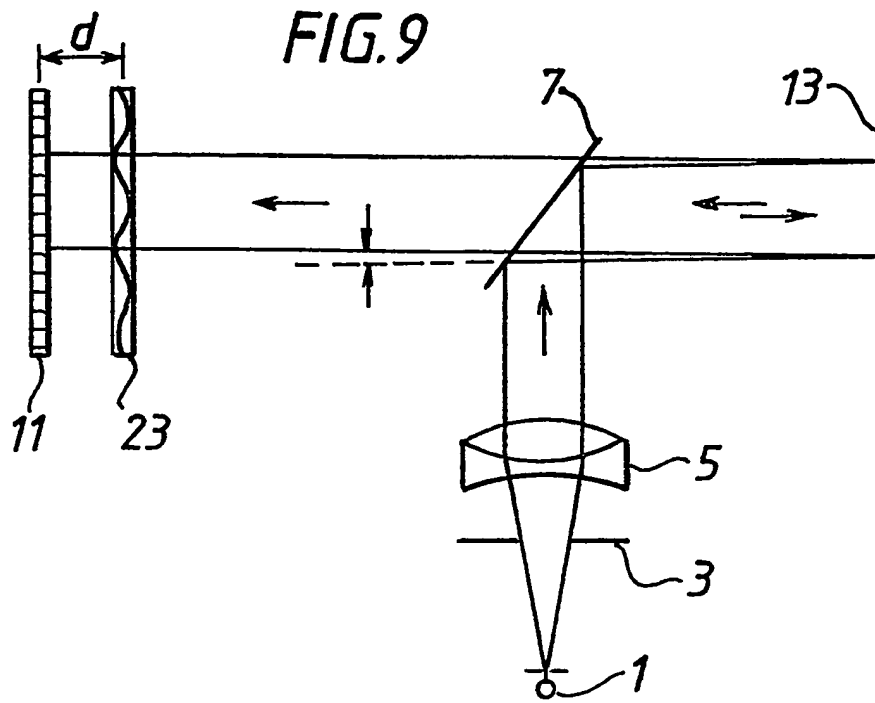
- 1 -

ANGLE DETECTION

The present application relates to the detection of the angle of a beam of light.

Systems for detecting the angle of a beam of light are used, for example, in devices for detecting the alignment of two parts of an apparatus or for detecting the flatness of an optical table or other table by measuring the relative alignment between different portions of the table. Similarly, they may be used for measuring the flatness of an optical slideway or of a machine bed.

In such systems, a beam of light is shone onto the surface the alignment of which is to be detected, and the angle of the reflected beam is detected. The angle of the reflected beam will provide a measure of the angle of the surface from which it is reflected. In practice, the beam is normally reflected not from the surface itself but from a mirror placed on the surface, in order to ensure a high quality specular reflection.

In a known system for measuring the angle of a light beam, a parallel-sided light beam is directed to an object and the reflected return beam is captured by a lens. The angle of the reflected

5 return beam is determined by placing a multi-element photodetector spaced from the lens by the focal length thereof. The reflected return beam will be parallel-sided, and as is well known, a parallel-sided beam is focussed by a lens to a

10 spot at a position one focal length from the lens, the position of the spot in the focal plane being determined by the angle of incidence of the parallel-sided beam. Accordingly, this arrangement creates a spot of light on the multi-element

15 photodetector at a position corresponding to the angle of the reflected return beam. The position of the spot can be detected from the output of the photodetector.

20 While the arrangement described above is highly accurate in theory, it is in practice limited by the quality of the optical elements used, and also by the characteristics of the multi-element photodetector. If the gemoetry is set up in a

25 theoretically perfect arrangement, the entirety of

the light from the reflected return beam is focussed on to a single element. The resolution with which the system can detect the angle of the light beam will depend on the pitch of the elements in the detector. In order to provide a good quality output signal, the elements must be able to withstand the light power of the fully focussed beam, and preferably will not saturate at this light intensity. In practice, the apparatus may be set up so that the light beam is not focussed precisely to a spot on the detector, so that the illuminated area covers more than one element. The position of the brightest part of the illuminated area can be detected by comparing the intensities of the signal outputs from all of the illuminated elements. A drawback to this arrangment is that the calculation is very dependent on the quality of the photodetector elements. This system is adversely affected by the failure of any one of the photodetector elements.

According to an aspect of the present invention there is provided an arrangement for detecting the angle of a light beam in which a repeating waveform pattern is created on a photodetector array, such

that a feature of the waveform, for example its shape, its wavelength or its phase, varies with the angle of the light beam. Accordingly, the angle of the light beam can be determined by appropriate processing of the output of the photosensor array. Because the pattern of light formed on the photosensor array is a repeating waveform, a relatively large number of photodetector elements contribute to the output, so that the accuracy of the measurement on any particular occasion is not highly dependent on the performance of a very small number of elements in the detector array. Additionally, the large number of photodetector elements allows a greater total optical power to contribute to the output signal than in a system which focusses the beam to a spot. This allows an improved signal to noise ratio.

In the preferred embodiments of the present invention, the size of the detector array can be expanded up to the limit of the area in which the repeating pattern is formed, so as to increase the number of elements contributing to the output, thereby improving the quality of the output signal

and further reducing the effect of variations in the performance of different detector elements.

In order to analyse the output signals from the photodetector, it may be useful to perform a Fourier transform on the output signal, for example by using a fast Fourier transform (FFT) procedure.

In one embodiment of the present invention a beam of light the angle of which is to be detected is caused to interfere with a reference beam, and the interference pattern is detected by a photodetector. The pattern of light and dark formed on the photodetector by the interference pattern will have a periodicity, and its wavelength will depend on the angle between the reference beam and the beam the angle of which is to be detected.

Alternatively, the beam the angle of which is to be detected may fall onto a photodetector array through one or more masks having a repeating pattern, for example a sinusoidal pattern of light and dark. The masks are spaced from one another,

or where only one mask is used this is spaced from the detector. This spacing means that the position at which the shadow of the first mask falls on the next mask or on the detector varies with the angle of the incident light. Where two masks are used this will affect the shape of the waveform of the resulting pattern formed on the detector, and in either case a phase property of the detector output will vary with the angle at which light is incident on the arrangement.

Where only a single mask is used, this may be provided on one surface of a block of glass or similar transparent material, and the CCD may be formed on or bonded to an opposed surface, so as to ensure dimensional stability of the arrangement.

In processing the output of the CCD, the value is determined of a parameter which varies with the angle of the beam of light. It may be possible to go on to apply the value of this parameter to an equation which has been predetermined from a knowledge of the features of the system to calculate the angle. However, it will often be more convenient to calibrate the system by

discovering the value of the parameter for light beams of known angles, thereby to form a look-up table which the system can use subsequently to determine the angle from the value of the parameter extracted from the photodetector output.

5

Embodiments of the present invention, given by way of non-limiting example, will now be described with reference to the accompanying drawings, in which:

10

Figure 1 shows schematically a first embodiment of the present invention;

Figure 2 shows a schematic close-up of the detector arrangement of the embodiment of Figure 1;

15

Figure 3 shows a processing circuit for processing the output of the photodetector array;

20

Figure 4 is a view corresponding to Figure 1, of a second embodiment of the present invention;

Figure 5 is a schematic close-up view of the detector arrangement of the embodiment of Figure 4;

5   Figure 6 shows a first physical structure for the detector assembly in the embodiment of Figures 4 and 5;

Figure 7 shows an alternative physical construction
10   of the detector assembly;

Figure 8 shows a further alternative physical construction for the detector assembly;

15   Figure 9 is a schematic view corresponding to Figure 1 of a third embodiment of the present invention;

Figure 10 is a schematic close-up view of the
20   detector arrangement of the embodiment of Figure 9; and

Figure 11 shows a modification for the embodiments of Figures 1, 4 and 9 to enable the angle of a

light beam to be detected along two mutually transverse axes.

Figure 1 shows schematically an arrangement of parts in a first embodiment of the present invention, and Figure 2 is schematic enlarged view of the detector portion of the apparatus of Figure 1.

In the arrangement of Figure 1, light from a light source 1 passes through a stop 3, a collimator lens 5 to fall on a beam splitter mirror 7. Part of the light is reflected by the beam splitter mirror 7 to an internal reference mirror 9, which returns it to pass through the beam splitter mirror 7 to a photodetector array 11. Typically, the photodetector array 11 is a charge-coupled device (CCD).

Light from the light source 1 which passes through the beam splitter mirror 7 passes to an external measurement mirror 13, which is mounted on a surface the alignment of which is to be measured. The light is reflected from the external measurement mirror 13 back to the beam splitter

mirror 7, which reflects it to the photodetector array 11. Accordingly, two beams of light reach the photodetector array 11, one from the internal reference mirror 9 and the other from the external

5   measurement mirror 13. By the use of coherent light, typically by providing the light source 1 as a laser, these two beams will interfere with each other. The resulting interference pattern is detected by the photodetector array 11.

10

Turning to Figure 2, successive wave fronts of the two beams of light are shown in broken lines, whereas the two beam directions are shown in unbroken lines. The angle between the two beams is

15   exaggerated as compared with Figure 1, for the purposes of illustration.

As can be seen in Figure 2, at the positions along the photodetector array 11 which are marked with

20   arrows in the Figure, the light from the two light beams will interfere constructively, and accordingly the photodetector array will be illuminated brightly at these points. These points are determined by the locations at which the wave

25   fronts in the different beams cross each other.

These points are the corners in the diamond-shape pattern shown in Figure 2. As will be appreciated, as the directions of the two beams of light become more similar, the diamond-shapes will become wider, and accordingly the points of constructive interference on the photodetector array 11 will become spaced further apart.

It can be seen that the pattern formed on the photodetector array 11 will be a pattern of alternating light and dark fringes, and that the wavelength of this pattern will vary with the angle between the two beams of light. As the beams of light become closer and closer to being parallel, the wavelength of the pattern on the photodetector array 11 will increase, and if the two waves are completely parallel this wavelength will be infinite. Since it becomes difficult to measure the properties of the waveform of the light and dark pattern formed on the photodetector array 11 when its wavelength becomes very long, the internal reference mirror 9 is provided so that the reflected beam from it is at a slight angle to the reflected beam from the external measurement mirror 13 when the external measurement mirror has the

perfect desired alignment. In this way, a measurable output is obtained from the photodetector array 11 when the surface on which the external measurement mirror 13 is placed is correctly aligned.

Conveniently, all of the parts shown in Figure 1 except for the external measurement mirror 13 can be provided as a unit in a common casing.

Figure 3 shows schematically the parts of a processing circuit for obtaining the angle of the light beam from the external measurement mirror 13 from the repeating pattern of light and dark formed on the photodetector array 11. In addition to the detector array 11, the system of Figure 3 comprises a processing unit 15, including program and working memory, a look-up table 17, an optional fast Fourier transform unit 19, and an output device 21 such as a display or a printer for providing the output information concerning the angle of the beam from the external measurement mirror 13. The fast Fourier transform unit 19 can be provided as a software package within the program memory of the

CPU 15 if desired. Fast Fourier transform units and software packages are well known.

There are a variety of ways in which the output signal from the CCD array 11 can be processed to obtain the desired angle information. In one simple method, the signal is processed by the CPU 15 in a manner which is well known, to provide a level-adjusted signal which passes above and below zero, and the points at which the signal crosses the zero level are determined. The wavelength of the pattern formed on the CCD array 11 can be obtained directly from the spacing between the zero-crossing points. As explained above, this wavelength is a measure of the angle of the external measurement mirror 13.

In an alternative method, which is presently preferred on the grounds of resolution and accuracy, the output signal from the photodetector array 11 is subjected to a fast Fourier transform by FFT unit 19, so as to be transformed into the spatial frequency domain, filtered, frequency shifted, and subjected to an inverse Fourier

transform. This process can be divided into five steps, as follows.

1) <u>Detecting interference fringes</u> Let $\underline{G}_m$ be the gradient of the phase front of the measurement beam at the detector plane, and $\underline{G}_r$ be that of the reference beam, and $\underline{p}$ the phase associated with the difference in the average optical path lengths of the two beams, the interference pattern $\underline{I}$ can be written as

$$I = a + b\cos(G_r x - G_m x + p) \qquad (1)$$
$$= a + b\cos(2\pi f_r x - 2\pi f_m x + p)$$

where $\underline{a}$ and $\underline{b}$ are real quantities and are dependent on the intensity distribution of the light beams; and $f_r = G_r/2\pi$, $f_m = G_m/2\pi$.

Equation (1) can be rewritten as

$$I = a + \tfrac{1}{2} b\exp[j2\pi(f_r - f_m)x]\exp jp \qquad (2)$$
$$+ \tfrac{1}{2} b\exp[-j2\pi(f_r - f_m)x]\exp -jp$$

where $j = \sqrt{-1}$. The output from the CCD array 11 would be essentially as shown in equation (2).

2) <u>Fourier transform</u> Taking the Fourier transform of the output of the CCD array 11 yields

$$
\begin{aligned}
F\{I\} \; = \; & F\{a + \tfrac{1}{2} \, b\exp[j2\pi(f_r - f_m)x]\exp jp \\
& + \tfrac{1}{2} \, b\exp[-j2\pi(f_r - f_m)x]\exp{-jp}\} \\
= \; & A(f_x) + \tfrac{1}{2} \, B(f_x - f_r + f_m)\exp jp \\
& + \tfrac{1}{2} \, B \, (f_x + f_r - f_m)\exp{-jp}
\end{aligned}
\tag{3}
$$

where <u>F</u> denotes the Fourier transform operation, <u>A</u> and <u>B</u> are the transformed functions of a and b, and <u>f</u>$_x$ is the spatial frequency variable. <u>B</u> is obtained by applying the convolution theorem of a Fourier transform and the sifting property of a Dirac-Delta function.

Graphically, equation (3) can be represented as a frequency distribution having peaks at $f_x = -(f_r - f_m)$, 0, and $+(f_r - f_m)$.

3) <u>Filtering</u> This is to select either the positive or the negative parts of the spectrum and is done by multiplying equation (3) by a filter function centred at $f_x = f_r$ and with an appropriate

5   bandwidth sufficient to include all expected values of $(f_r - f_m)$ but exclude $f_x = 0$. The resulting filtered spectrum $\underline{I}_f$ is therefore

$$I_f = \frac{1}{2} B(f_x - f_r + f_m)\exp jp \qquad (4)$$

10

4) <u>Shifting</u> The spatial frequency value in equation (4) is shifted by an amount equal to $\underline{f}_r$ to provide a shifted spectrum $\underline{I}_s$ of

15

$$I_s = \frac{1}{2} B(f_x + f_m)\exp jp \qquad (5)$$

5) <u>Inverse Fourier Transform</u>   Taking the inverse Fourier transform of equation (5) yields the inverse function $\underline{I}_o$

$$I_o = F^{-1} \{ \frac{l}{2} B (f_x + f_m) \exp jp \} \tag{6}$$

$$= \frac{l}{2} b \exp j[2\pi f_m x + p]$$

$$= \frac{l}{2} b \exp [G_m x + p]$$

Since <u>b</u> is entirely real, the only phase term is contained in the exponential function. The tilt of the measurement beam therefore is given by the gradient $\underline{G}_m$ of the linear term in the phase of the inverse Fourier transform. Note that with an FFT routine, the resultant is in the form of real and imaginary parts. The phase, and hence its linear gradient can be determined easily.   The angle of the external measurement mirror 13 can be obtained from the gradient $\underline{G}_m$ by reference to the geometry of the optical system.

Both in the case where the wavelength of the signal
on the photodetector array 11 is extracted from
zero-crossing information and in the case where the
gradient of the linear term in the phase of an
5   inverse Fourier transform signal is extracted, it
is theoretically possible to derive a formula for
converting the extracted signal into the angle of
the external measurement mirror 13, by knowledge of
the optical properties of the apparatus.   However,
10   it will normally be more convenient in practice to
perform a calibration operation on the apparatus
after it has been constructed, in which values of
the extracted signal are determined for a variety
of known angles of the external measurement mirror
15   13, and from this a table relating the value of the
extracted signal to the angle of the mirror 13 can
be constructed. Such a table is then stored as the
look-up table 17, and the CPU 15 uses the look-up
table 17 to obtain angle information corresponding
20   to the extracted wavelength value or inverse
Fourier transform phase signal value.   The angle
value thus obtained is provided to the output unit
21.

Typically, a CCD array used as the photodetector array 11 may have, for example, 2048 cells or 4096 cells, at a pitch of, for example, 10 micrometres. Thus the total length of the array will be of the

5   order to a few centimetres. The portion of the array on which the interference pattern is formed may be very much longer than the wavelength of the interference pattern as formed on the array, so that there are many cycles of the repeating pattern

10   formed on the array 11. Accordingly, if any individual CCD cell fails or provides a non-standard output, this has a very small effect on the reliability of the output angle measurement.

15

The zero-crossing signal processing method described above has a good property of resisting the effects of variations in the intensity of light across the beam. If the Fourier transform signal

20   processing method is used, variations of light intensity across the beam may create additional terms in the initial Fourier transform output. However, provided that the intensity is uniform over a distance of the order of magnitude of the

25   wavelength of the pattern of light and dark formed

on the photodetector array 11, such components in the Fourier transform signal will easily be rejected.

5   In the arrangement of Figures 1 and 2 the component parts should be stable during the measurement operation. If, for example, there was any movement of the external measurement mirror 13 while the exposure of the photodetector array 11 was taking

10   place, the pattern on the photodetector array 11 would move and so the pattern as detected would be blurred. In order to minimise any difficulties of this type, it is preferred to have a very fast exposure of the photodetector array 11, for example

15   by employing a single shot laser system in the light source 1.

As has been mentioned above, the interference-based system of Figures 1 and 2 requires a parallel-sided

20   beam of coherent light. Another constraint is that optical impurities, such as a speck of dust on one of the mirrors, will create interference fringes which will increase the background noise in signal read from the photodetector array 11.

Accordingly, the system must be kept clean and be operated in a clean environment.

Figures 4 and 5 are views corresponding to Figures 1 and 2, of a second embodiment which avoids the need to create an interference pattern.

In the arrangement of Figures 4 and 5, a light source 1, a stop 3, a collimator lens 5 and a beam splitter mirror 7 are provided as in Figure 1, except that the light from the light source 1 does not need to be precisely parallel-sided nor coherent, and therefore a variety of other light sources are usable in addition to a laser.

In this system, there is no internal reference mirror, light from the light source 1 is reflected by the mirror 7 to be directed onto the external measurement mirror 13, and the light returning from the external measurement mirror 13 passes through the mirror 7 to the photodetector array 11. Mounted in front of the photodetector array 11, so that the light from the external measurement mirror 13 falls onto it, are two shadow gratings or masks 23, 25, a distance d_1 apart. The nearer mask 25 is

a distance $\underline{d}_2$ from the photodetector array 11. Each

of these masks has a repeating pattern of varying

light transmissivity. For example, each mask may

vary between substantially entirely transparent and

5   substantially entirely opaque in a sine wave cycle.

This sine wave variation in transmissivity is

indicated schematically in Figures 4 and 5 by the

undulating line shown in each of the masks 23 and

25.

10

As the light reflected from the external

measurement mirror 13 falls on the photodetector

array 11 through the masks 23, 25, a shadow of each

mask will be formed on the photodetector array 11.

15   Each shadow will be an alternating pattern of light

and dark, having a waveform and a wavelength in

accordance with the mask concerned. The final

pattern of light and dark actually formed on the

photodetector array 11 will be a composite of the

20   shadows from both of the masks 23, 25.

As can be seen from Figure 5, a ray of light which

passes through one particular point on the first

mask 23 will pass through a point on the second

mask 25 which is determined by the angle of the ray of light. In Figures 4 and 5 the masks are shown as having patterns of the same wavelength, and in phase with each other for light perpendicular to the masks and the photodetector array 11. The superimposition of the shadows of the two masks 23, 25 will create a pattern of light and dark on the photodetector array 11 having a formula which is the product of multiplying together the formulae of the two masks 23, 25. The masks will be multiplied together without any offset if the direction of incident light is perpendicular to the masks 23, 25 and the photodetector array 11. However, where the light is angled from the perpendicular the formulae of the masks will be multiplied together with a distance offset equal to $d_1 \tan a$ where a is the angle between the direction of the light and the perpendicular to the masks 23, 25, and the product will itself be offset relative to the photodetector array 11 by $d_2 \tan a$. These distance offsets will represent phase offsets in the equation for the masks, according to what proportion of the wavelength L of the mask pattern is represented by each distance offset.

If the transmissivities T1 and T2 of the masks 23, 25 are both given by:

$$T1 = T2 = 1 + \cos X \qquad (7)$$

5

where $\underline{X}$ is the normalised distance along the masks 23, 25, (i.e. $X = 2\pi$ where the distance is one wavelength $\underline{L}$ of the mask pattern) the pattern of light $\underline{S}$ on the photodetector array 11 is given

10 by:

$$S = T1 \times T2 = [1 + \cos(X+k_2)] .$$

$$[1 + \cos(X+k_1+k_2)] \qquad (8)$$

15 where $\underline{k_1}$ is the phase offset between the shadows of the patterns of the masks 23, 25 resulting from the slant of the light, and $\underline{k_2}$ is the phase offset of the shadow of the pattern of the nearer mask 25 on the photodetector array 11. The phase offsets $\underline{k_1}$

20 and $\underline{k_2}$ are related to the spacings $\underline{d_1}$ and $\underline{d_2}$ by the formulae:

$$k_1 = (2\pi d_1 \tan a)/L \tag{9}$$

$$k_2 = (2\pi d_2 \tan a)/L \tag{10}$$

where $\underline{a}$ is the angle by which the light differs from the perpendicular to the masks 23, 25, and $\underline{L}$ is the wavelength of the transmissivity pattern of each of the masks 23, 25.

Multiplying out equation (8) gives:

$$S = 1 + \cos(X+k_2) + \cos(X+k_1+k_2) \tag{11}$$
$$+ \cos(X+k_2).\cos(X+k_1 k_2)$$

and applying trigonometric identities gives:

$$S = 1 + \frac{1}{2} \cos k_1 \tag{12}$$
$$+ 2\cos(k_1/2).\cos(X+k_2+k_1/2)$$
$$+ \frac{1}{2} \cos(2X+2k_2+k_1)$$

It can be seen that the phase offset $\underline{k}_1$ appears in the dc offset level of the output of the photodetector array 11 and the amplitude of the first harmonic (cosX) term, and both the phase

5   offsets $\underline{k}_1$ and $\underline{k}_2$ appear in the phase of both the first harmonic (cosX) and the second harmonic (cos2X) terms.

If a fast Fourier transform is performed on the

10   output of the photodetector array 11, the output will be in the form of the amplitude of the dc component and the amplitude and phase of the harmonics. Since the phase information depends on $(k_2 + k_1/2)$, the conversion of this into

15   information about the angle $\underline{a}$ depends on the values of both $\underline{d}_2$ and $\underline{d}_1$. If the amplitudes of the dc component and the first harmonic are used, the conversion of this into information about the angle $\underline{a}$ depends only on the value of spacing $\underline{d}_1$, and the

20   precise value of $\underline{d}_2$ does not matter.

As described above with reference to the first embodiment, the information obtained by Fourier transform processing is most conveniently converted into information relating to the angle of the light beam by reference to the look-up table 17, compiled by a calibration process.

As can be seen from equation (9), for any given value of the angle a, the value of k_1 is directly proportional to the separation d_1 between the two masks 23, 25. Therefore the sensitivity of the device can be increase by increasing the spacing d_1. However, this will also reduce the range of angles of light for which the apparatus can be used, since any value of k_1 outside the range $+\pi$ to $-\pi$ cannot be distinguished from a corresponding value inside this range. Accordingly the device should only be used to detect angles inside this range, unless some further arrangement is provided to distinguish between different angles resulting in the same phase offset k_1.

For a CCD array as previously described with reference to the first embodiment, the separation $\underline{d}_1$ between the masks 23, 25 will conveniently be around 4 to 5mm, although it can be up to about 5cm. The separation $\underline{d}_2$ between the photodetector array 11 and the closer mask 25 can conveniently be a few mm, or up to about 5cm.

In the example described above, the patterns of the two masks 23, 25 had the same frequency and were in phase. This is not necessary, but if they have different frequencies there will be additional terms in equation (12) above. In this case, the processing circuit of Figure 3 should identify and separate out the terms in the Fourier transform output which vary with the angle $\underline{a}$.

For the CCD type and mask spacing given above, the wavelength of the repeating transmissivity pattern of each mask will typically be of the order of 50μm. As a general constraint, the wavelength of the mask pattern should be greater than the pitch of 2 cells of the CCD, but does not need to be very much greater. The figure of 50μm for the mask

pattern wavelength compared with 10μm for the CCD element pitch, so that one is five times the other, is suitable in practice.

Figure 6 shows one possible construction for the detector assembly of the photodetector array 11 and the masks 23, 25 in the embodiment of Figures 4 and 5. In Figure 6 first and second light transmissive elements 27, 29 and the photodetector array 11 are supported and held rigidly in position by rigid side pieces 31. The transmissivity patterns forming the masks 23, 25 are formed on the surfaces of the respective light transmissive elements 27, 29, and the side pieces 31 hold the two masks 23, 25 apart from the distance d_1.

Some difficulty may arise with the construction of Figure 6, owing to the need for very good mechanical stability in the detection assembly. With a CCD having 4096 cells at a 10μm pitch, the masks being separated by a distance d_1 of about 5mm and the wavelength of the mask pattern being about 50μm, movements of the order of 10nm in the pattern of one of the masks 23, 25 relative to the other

can be detected by the method described above of determining the phase of components in the CCD output by performing a Fourier transform. Accordingly, the positioning of the two masks 23, 25 relative to each other in the longitudinal direction of the masks 23, 25 and the photodetector array 11 must be stable and non-varying to within a significantly smaller distance than this, preferably to within less than 1nm. This is because the system cannot distinguish between changes in the angle of the light and relative movement between the two masks 23, 25. Such a very high degree of mechanical stability can be difficult to obtain with the arrangement of Figure 6.

An alternative construction for the detector assembly is shown in Figure 7. In this construction, a single light transmissive element 33 is provided, and the masks 23, 25 are provided by modifying the light transmissivity of respective opposed surfaces of the single light transmissive element 33. Accordingly, the distance d_1 between the two masks 23, 25 is defined by the thickness of

the single light transmissive element 33. The side
pieces 31 act to hold the single light transmissive
element 33 to the photodetector array 11.

The construction of the detector assembly can be
further simplified and the physical stability of
the assembly can be conveniently provided by the
arrangement shown in Figure 8, in which the
photodetector array 11 is bonded directly to the
single light transmissive element 33 or
alternatively is formed directly on the single
light transmissive element 33 as a substrate. The
single light transmissive element 33 can be glass
or any other transparent material suitable for use
as a substrate in the process for forming the
photodetector array 11.

In order to provide both of the masks 23, 25 using
the detector assembly of Figure 8, the second mask
25 may be provided on the surface of the single
light transmissive element 33 on which the
photodetector array 11 is provided. However, this
may lead to complications in manufacture, and in
particular it may be difficult to provide the
second mask 25 if the photodetector array 11 is to

be formed directly on the single light transmissive element 33 as a substrate. Accordingly, the detector assembly of Figure 8 is more conveniently used in an embodiment of the present invention having only one variable transmissivity mask 23, which can be formed on the surface of the light transmissive element 33 remote from the photodetector array 11.

Figures 9 and 10 illustrate a third embodiment of the present invention, in which only one variable light transmissivity mask is used.

The arrangement of Figures 9 and 10 is the same as the arrangement of Figures 4 and 5 except that only one mask 23 is present. Accordingly, the pattern of light and dark formed on the photodetector array 11 is the same repeating pattern as the pattern of the mask 23. As can be seen from Figure 10, the position at which the shadow of any particular point on the mask 23 appears on the photodetector array 11 depends on the angle of the light reflected from the external measurement mirror 13. Accordingly the phase, with respect to the photodetector array 11, of the pattern of light and

dark formed on the photodetector array 11 will vary with the angle of the light, and the processing circuit of Figure 3 is used to determine that phase. In this case, the critical separation $\underline{d}$ is the spacing between the mask 23 and the photodetector array 11, as shown in Figures 9 and 10.

As in the embodiment of Figures 4 and 5, the phase offset $\underline{k}$ between the shadow pattern formed on the photodetector array 11 and the pattern of the mask 23 is defined by:

$$k = (2\pi d \tan a)/L \qquad (13)$$

where $\underline{L}$ is the wavelength of the pattern of the mask 23 and $\underline{a}$ is the angle by which the light varies from being perpendicular to the mask 23 and the photodetector array 11.

If the transmissivity $\underline{T}$ of the mask 23 is given by:

$$T = 1 + \cos X \qquad (14)$$

where X is distance along the mask 23 normalised with reference to L , the pattern S of light on the photodetector array is given by:

$$S = 1 + \cos(X+k) \qquad (15)$$

where k is the phase offset.

One possible way of determining k is to form the Fourier transform of S, using the fast Fourier transform unit 19, and select a component having the frequency of the mask pattern. The phase term of this component will contain $k.$

It may be noted that since the spatial frequency of the desired harmonics are known in advance, it is not necessary to compute the Fourier transform for all the spatial frequency values but only for those which are wanted, although in this case certain values for the wavelength of the sinusoidal mask pattern will be preferable. In the embodiment of Figure 9, only the component having the spatial frequency of the mask pattern is needed, and therefore it may be

possible to obtain the desired phase information from only a single integration operation. This would reduce the processing time required, and could also enable simplified hardware, as compared with a system which computed the full fast Fourier transform.

In an alternative method, the output of the photodetector array 11 may be multiplied in the CPU 15 by <u>cosX</u> and separately by <u>sinX</u> as follows. Multiplying by <u>cosX</u> gives:

$$S \cos X = \cos X [1 + \cos(X+k)] \qquad (16)$$

$$= \cos X + \cos X . \cos(X+k)$$

$$= \cos x + \frac{1}{2} \cos(2X+k) + \frac{1}{2} \cos k \qquad (17)$$

while multiplying by <u>sinX</u> gives:

$$S \sin X = \sin X [1 + \cos(X+k)] \qquad (18)$$

$$= \sin X + \sin X . \cos(X+k)$$

$$= \sin X + \frac{1}{2} \sin(2X+k) - \frac{1}{2} \sin k \qquad (19)$$

It can be seen from equations (17) and (19) that if the results of multiplying the output of the photodetector array 11 by <u>cosX</u> and by <u>sinX</u> are

each filtered to remove the varying terms and
retain only the dc term, values can be obtained for
cosk and sink . The ratio of these will provide
tank . The CPU 15 can be provided with a table of

5   tan values to enable it to determine the value of k
from tank , or alternatively the look-up table 17
can be configured so that values of tank can be
input to it directly. This method may require more
computing power than the method using a Fourier

10   transform.

If a CCD array of 2048 elements having an element
pitch of 13μm is used as the photodetector array
11, the wavelength of the pattern on the mask 23 is

15   52μm and the spacing d between the mask 23 and the
photodetector array 11 is 4cm, the applicants
estimate that tilt angles of the external
measurement mirror 13 can be measured with an
uncertainty, owing to theoretical considerations of

20   photon noise, of the order of 0.005 seconds of
arc.

As with the embodiment of Figures 4 and 5, the
accuracy can be increased by increasing the

25   separation d . However, even if the physical

stability of the detector system is ensured, there is a limit to the extent to which the spacing d can be increased. If the other parameters of the system are as set out above, spacings d of more than about 10cm will result in a significant amount of noise appearing in the output signal from the photodetector 11, caused by the diffraction grating effect of the mask 23.

As with the embodiment of Figures 4 and 5, the maximum available range of measurement is limited because a shift of the pattern on the photodetector array 11 by more than L/2 (where L is the wavelength of the pattern of the mask 23) cannot be distinguished from a shift falling within that range caused by a different angle of the light beam. This is not necessarily a problem, since systems of this type are normally only used for measuring very small deviations from the desired direction, and if the external measurement mirror 13 is tilted away from its desired direction by a large angle, the reflected beam may miss the detector assembly entirely. However, if it is desired to increase the measurement range of the

system, means can be provided to enable successive cycles in the value of $\underline{k}$ to be resolved.

One way of providing such an arrangement is to modify the transmission characteristics of the mask 23 to superimpose a further sine wave pattern of light and dark on it, having a much longer wavelength than the pattern used for accurate angle measurement. In this case, the transmission function T of the mask 23 is given by:

$$T = 1 + \cos X + \cos(X/N) \tag{20}$$

where $\underline{N}$ is the factor by which the wavelength of the additional pattern is greater than the wavelength of the pattern used for accurate angle measurement.

If a Fourier transform method of detecting phase shift is used, the components provided by the respective superimposed sine patterns can easily be distinguished from each other, as they will have substantially different frequencies. The phase offset for the long frequency pattern will provide an unambiguous approximate measurement of the

angle, while the phase offset of the short wavelength pattern will provide a more accurate measurement of the approximately determined angle.

Using the parameters for the system as set out above, the applicants estimate that in the absence of an additional longer wave pattern in the mask 23, the system can be used to measure tilt of the external measurement mirror 13 in the range + or - 67 seconds of arc, but if a further pattern is provided in the mask 23, having a wavelength of 1.644mm, the maximum measurement range can be increased to + or - 2100 seconds of arc in the tilt of the external measurement mirror 13. This is accompanied by a slight increase in the uncertainty of the measurement, of the order of about $\sqrt{2}$.

In the embodiments of Figures 4 and 5 and Figures 9 and 10, the light from the light source 1 does not need to be coherent and the beam of light obtained from it does not need to be precisely parallel-sided. The intensity distribution of light across the beam does not need to be uniform, although it should be reasonably uniform over

distances of the order of magnitude of the transmissivity pattern of the mask or masks 23, 25 used.

5   The systems described above are one-dimensional systems, in the sense that they detect the angle of tilt of the received beam of light, and thereby the external measurement mirror 13, along one axis only. The systems can be converted into
10   two-dimensional systems, which detect the angle of tilt along two axes, in the manner shown in Figure 11.

     In Figure 11, the light leaving the beam splitter
15   mirror 7 towards the detector falls on a second beam splitter mirror 35. Part of the light passes through the second beam splitter mirror 35 and part is reflected by it. The part which passes through the second beam splitter mirror 35 falls on a first
20   detector assembly 37, which extends linearly in one direction, and the reflected part of the light falls on a second detector assembly 39 which extends linearly in a different direction so as to detect changes in the angle of the light along an
25   axis generally perpendicular to the axis of change

detected by the first detector assembly 37. Each of the detector assemblies 37, 39 can be as shown in Figure 2, in Figure 5 or in Figure 10, depending on which of the detection arrangements is being used.

In order to provide two dimensional information, the light beam should have a cross-sectional area with a substantial extent in perpendicular directions, for example the cross-sectional shape can be generally square or generally circular. In order to concentrate this light onto the generally long, thin photodetector array 11 in each detector assembly 37, 39, respective cylindrical lenses 41, 43 are provided.

In the two-dimensional arrangement of Figure 11, a separate processing circuit as shown in Figure 3 can be provided for each of the detector assemblies 37, 39. Alternatively, a single common processing circuit may be used which processes the two outputs independently. This may output to the output unit 21 angles of tilt in the the two axis directions, or alternatively the CPU 15 may then combine the two angles geometrically to provide an output in

the form of a magnitude of tilt and a direction of tilt.

The above embodiments have been provided by way of example, and various modifications and alternatives will be apparent to those skilled in the art.

CLAIMS

1. A system for detecting the angle of a light beam comprising photodetector means and optical means for causing the light beam to form on the photodetector means a pattern of light having a waveform property which varies with the angle of the light beam.

2. A system according to claim 1 in which a wavelength of the pattern of light varies with the angle of the light beam.

3. A system according to claim 1 in which a phase of the pattern of light varies with the angle of the light beam.

4. A system according to any one of claims 1 to 3 in which the said beam of light is caused to interfere with a reference beam of light having a reference direction, and an interference pattern thereby created is formed on the photodetector means.

5. A system according to any one of claims 1 to 3 in which the said beam of light passes through at least one mask having a transmissivity pattern in which transmissivity through the mask varies

5   periodically with distance along it to project the pattern onto the photodetector means.

6. A system according to claim 5 in which the said beam of light passes through first and second masks

10   to project a composite pattern on the photodetector means.

7. A system according to claim 5 in which the said beam of light passes through a said mask and

15   projects an unmixed pattern of it on the photodetector means.

8. A system for detecting the angle of a light beam comprising means to form a reference beam

20   having a reference direction which interferes with the said light beam, detector means to detect the interference pattern, and means to obtain a measure of the angle of the light beam from a waveform property of the output of the detector means.

25

9. A system according to claim 8 in which the said light beam and the reference beam are divided from a common beam of coherent light, and the light beam is then directed to a reflector so that the angle of the light beam depends on the angle of the reflector.

10. A system for detecting the angle of a light beam in which the beam is passed through first and second spaced apart masks before falling on detector means, the first and second masks each having a respective pattern of transmissivity which varies periodically with distance along the mask.

11. A system according to claim 10 in which a composite image of the first and second masks is formed on the detector means, and the output of the detector means is processed to determine the relative phase between the image of the first mask in the composite image and the image of the second mask in the composite image.

12. A system according to claim 11 in which the said images comprise shadows of the masks.

13. A system for detecting the angle of a light beam in which the beam passes through a mask, having a pattern of transmissivity which varies periodically with distance along the mask, before

5 falling on a detector means.

14. A system according to claim 13 in which an image of the mask is formed on the detector means and the output of the detector means is processed

10 to determine the phase of the image relative to the detector means.

15. A system according to claim 14 in which the image of the mask comprises a shadow thereof.

15

16. A method for detecting the angle of a light beam comprising:

        (a) forming on a detector means a pattern of light having a waveform property which varies with

20 the angle of the light beam,

        (b) performing a Fourier transform on the output of the detector means,

        (c) obtaining from the Fourier transform at least one frequency component, and

25   (d) extracting from the frequency component

a part which provides a measure of the said waveform property.

17. A method according to claim 16 in which the step of obtaining at least one frequency component comprises selecting at least one component from the Fourier transform.

18. A method according to claim 16 or claim 17 in which the step of obtaining at least one frequency component comprises frequency-shifting a component from the Fourier transform.

19. A method according to claim 18 in which the step of obtaining at least one frequency component comprises performing an inverse Fourier transform on the frequency-shifted component.

20. A method according to any one of claims 16 to 19 in which the said extracted part of the frequency component is a phase part.

21. A system for detecting the angle of a beam of light substantially as herein described with reference to the drawings.

22. A method for detecting the angle of a beam of
light substantially as herein described with
reference to the drawings.

Patents Act 1977
Examiner's report to the Comptroller under Section 17 (The Search Report)

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Relevant Technical fields

(i) UK Cl (Edition   K   )   G1A(ACA,ACE,AEA,AEE,AEK, AES,AEX)

(ii) Int CL (Edition   5   )   G01B, G01D

Databases (see over)

(i) UK Patent Office

(ii)

Search Examiner

K SYLVAN

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Documents considered relevant following a search in respect of claims   1−22

Category (see over)	Identity of document and relevant passages	Relevant to claim(s)
X	GB 2129245 A (PERKIN-ELMER) see whole document	1,3,5,7, 13−15
X	GB 1307431 A (SEC. DEFENCE) see Figure 1, and page 2 line 121 to page 3 line 13	1,3,5,6
X	EP 0405462 A1 (CSELT) see page 3 line 38 to page 4 line 15	1,2,4,8
X	EP 0220046 A2 (PILKINGTON) see Figure 1, and page 8 line 6 to page 10 line 7	1,3,4,8
X	WO 89/00674 A1 (POLYMETRIC) see Figures 2,3 and page 8 line 25 to page 10 line 10	1,2
X	US 4662750 A (BARGER) see Figure 1, and column 5 line 7 to column 7 line 45	1,4,8,9

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Category	Identity of document and relevant passages	Relevant to claim(s)

Categories of documents

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